ENHANCING MARINE ENERGY COMPETITIVENESS: CO-LOCATED OFFSHORE WIND AND WAVE ENERGY FARMS

S. Astariz[1] and G. Iglesias[2]

If marine energy is to become a viable alternative to fossil fuels, its competitiveness must be enhanced. In this sense, combining various renewables in the same marine space is emerging as a solution. Among the different options, this paper focuses on combined wind and wave energy farms. First, the different synergies between both renewable are analysed, such as the more sustainable use of the marine resource or the opportunity to reduce costs of both technologies by sharing some of the most important costs of an offshore project. Second, this paper focuses on two technology synergies: the reduction of the inherent intermittency of renewables; and the so-called shadow effect which implies the reduction of the wave height in the inner part of the wind farm. Both effects may suppose an important reduction in the operation and maintenance cost by reducing the balancing cost when connecting the installation to the grid and increasing weather windows to access the wind turbines. However, the benefits of this combination will depend on the site characteristics and the array layout. On this basis, the power smoothing and shadow effect in co-located farms are analysed through different case studies considering real sea conditions, wind farms currently in operation and a high resolution numerical model (SWAN). Finally, conclusions about the economic benefits of co-located farms are drawn by recalculating the levelised cost of energy when both renewable are combined.

Keywords: Wave energy; Wind energy: Co-located wind-wave farm; Synergies; Weather windows for O&M; Power smoothing.

1. INTRODUCTION

Wave and offshore wind energy are both part of the Offshore Renewable Energy (ORE) family which has a strong potential for development (Bahaj, 2011; Iglesias and Carballo, 2009) and is called to play key role in the EU energy policy, as identified by, e.g. the European Strategic Energy Technology Plan (SET-Plan). The industry has established, as a target for 2050, an installed capacity of 188 GW and 460 GW for ocean energy (wave and tidal) and offshore wind, respectively (Moccia et al., 2011). Given that the target for 2020 is 3.6 GW and 40 GW respectively, it is clear that a substantial increase must be achieved, in particular in the case of wave and tidal energy.

Sharing the same hostile marine environment, wave and offshore wind energies face similar challenges. However, their level of technological development is not the same. Whereas offshore wind is a proven technology, with 3.8 GW of installed capacity in Europe and employing 35,000 people directly and indirectly at the end of 2011 (EWEA, 2012), wave energy is still at an early stage of development.

A sustainable development of wave and offshore wind industries requires an efficient planning and use of the natural resources, i.e. one that optimises their exploitation safeguarding the natural environment. Taking advantage of different ocean renewable resources in the same offshore installation is gaining importance (Perez-Collazo et al., 2015) as a way to make these novel renewables cost-competitive (Allan et al., 2011). Among the different possibilities, this paper focuses on the combination of wave and wind energy installations (Astariz & Iglesias, 2015a).Wave production might compensate for the intermittency of offshore wind, while economies of scale developed from offshore wind could accelerate the cost reduction for the wave component. Moreover a reduced capital cost per MW installed may be achieved because of common elements like the electrical installation. In the same way, cost savings in maintenance tasks are expected due to sharing strategies and other factors such as the shielding effect of Wave Energy Converters (WECs) over the offshore wind farm (Astariz & Iglesias, 2015b), which increases the weather windows for O&M.

The aim of the present paper is to introduce the singularities of integrating wave energy into a conventional offshore wind farm through different pro-posed co-located wind-wave farms at some operating wind farms – Alpha Ventus, Bard, Horns Rev and Lincs. First, the positive synergies between both energies are outlined. Second, the different combined wave-wind systems are classified. Third, the benefits of co-located farms are studied through different case studies. Finally, conclusions are drawn, in particular regarding the energy cost.

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[1] EPS, Hydraulic Engineering, University of Santiago de Compostela, Campus Univ. s/n, Lugo, 27002, Spain
[2] School of Marine Science and Engineering, Plymouth University, Marine Building, Drake Circus, Plymouth, PL4 8AA, UK

2. SYNERGIES BETWEEN WAVE AND WIND ENERGY

Apart from the two main reasons to consider the combination of wave and offshore energy systems already drafted in the introduction i.e. an increased sustainability of the energy resources and the cost reduction of both energy sources there are a number of other synergies which arises when this combination is considered (Perez-Collazo et al., 2013). Furthermore, there are also a number of technology development issues which also arises from this possibility.

For its part, the combination of marine energies will increase the global energy yield per unit area of marine space, contributing to a better use of the natural resources. Moreover, the wave resource is more predictable and less variable than the wind resource (Veigas et al., 2014), and the combination of both will reduce the system balancing costs, as seen in (Chozas et al., 2012). For the same weather system the wave climate peaks trail the wind peaks (Chozas, 2013). In consequence, a combined exploitation will result in a reduction of sudden disconnections from the electric grid, an increase in availability (thus reducing the number of hours of non-activity) and a more accurate output forecast. Furthermore, the combined production of electricity using a shared grid infrastructure would become an important factor in reducing energy costs (Musial & Ram, 2010). In the same sense, the dimensions and special characteristics of offshore renewable energy projects require the use of expensive specialist marine equipment and facilities, such as port space or installation vessels. A combined project where these are shared would also contribute to reducing the costs.

In addition, the situation and accessibility conditions of the offshore energy projects makes it necessary to use dedicated installations by specialised technicians to ensure an effective O&M and to minimise the non-working times of the equipment. The combination of both energies would lead to an important cost reduction as result of the shared use of these installations and technicians. Moreover, it is clear that the energy extraction of an array of WECs creates a wake that modifies the local wave climate by reducing the mean wave height – the shadow effect (Carballo & Iglesias, 2013). Combining WECs and offshore wind parks at the same location, in a way in which this shadow effect can be used to obtain a milder wave climate inside the park (with the proper design, e.g., by locating the WECs along the perimeter of the offshore wind park), may lead to more weather windows for accessing the wind turbines for O&M, and to reduced loads on the structures.

Finally, the environmental impacts of wave and offshore wind energy are a major consideration in the development of these renewables (Abanades et al.2014). The combined option presents an important advantage in environmental terms in that it is likely to have a reduced impact (relative to independent installations), leading to a better utilisation of the natural resources.

3. WAVE-WIND SYSTEMS

There are different possibilities for a combined wave and wind array (Figure 1): (i) co-located wave and offshore wind turbines, (ii) hybrid energy converters; and (iii) energy islands (Astariz et al., 2015a). The former, which is the direct option at the current stage of development of both technologies, consists in combining an offshore wind farm with a WEC array with independent foundation systems but sharing the same marine area, grid connection, O&M equipment and personnel, etc. This way, no major technology developments are required and the integration consists essentially in appropriate grid planning. Within this combined arrays, different options can be considered (Astariz et al., 2015b) (Figure 1): (i) a Peripherally Distributed Array (PDA), where WECs are placed on the perimeter of the wind farm as a barrier; (ii) an Uniformly Distributed Array (UDA), with WECs deploying uniformly throughout the wind farm; or (iii) a Non-uniformly Distributed Array (NDA).

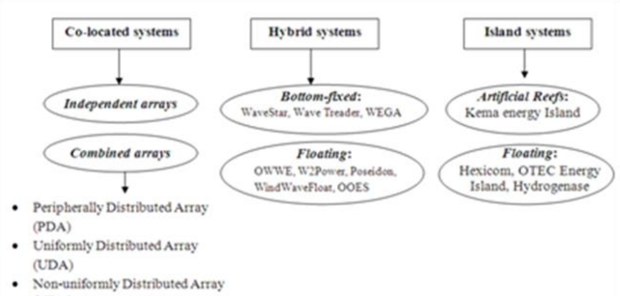

Figure 1. Classification of combined wave-wind technologies.

4. BENEFITS OF CO-LOCATED FARMS

4.1 Savings by shared elements

The Alpha Ventus wind farm (Figure 2) was selected as baseline scenario. It is located about 45 km north of the island of Borkum (Germany), at an approx. water depth of 30 m. This wind farm is composed by 12 wind turbines: 6 AREVA turbines with a tripod substructure and 6 Repower 5M turbines with a jacket-frame substructure – with a spacing between turbines of around 800 m, covering an area of 4 km^2 (Astariz & Iglesias, 2015a).

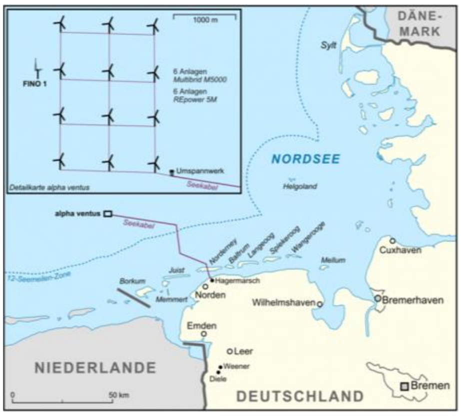

Figure 2. Alpha Ventus location.

Four co-located layouts (Figure 3) were proposed in this work on the basis of previous studies (Astariz & Iglesias, 2015a). In all cases, the WEC considered was WaveCat (Iglesias et al., 2011), a floating offshore WEC whose principle of operation is wave overtopping. The wave trans-mission coefficient was based on the tests carried out with a model at 1:30 scale to determine the wave field-WEC interaction. The nominal power at 1:1 scale is expected to be 1.2 MW. The spacing between devices was 198 m, which corresponds with the minimum spacing allowed –2.2D, where D = 90 m is the distance between the twin bows of a single WaveCat (Iglesias et al., 2011).

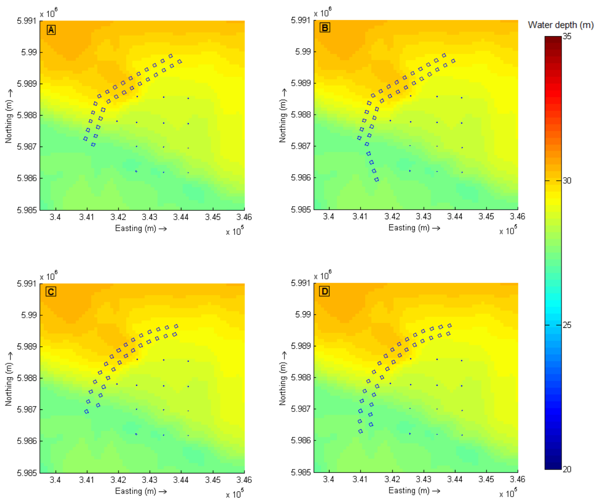

Figure 3. Co-located farm layouts. Configurations A to D and FINO1 research platform included. Values of the water depth (m).

Combined different energy sources involve cost-savings because of common elements and coordinated strategies. The cost of preliminary studies will be reduced by 60% (Astariz et al., 2015a) since the location is al-ready studied and characterised, and even part of the design is common, such as the electrical grid. The cost of licenses and permitting is dependent on the installed power, so it is going to be different for each configuration but independent of considering or not the wind farm. Also, the cost of WECs and mooring system would be the same. However, the largest savings would be achieved in the electrical connection, since the offshore station and the export cable can be the same for both installations. With these considerations, reductions in the capital cost between 12 and 14% were obtained.

4.2. Savings by common O&M strategies

As for the wind turbines, the O&M strategy in Alpha Ventus wind farm is based on workboats, and their cost is in the range 10-28 €/MWh (Blanco, 2009). Table 1 shows the breakdown of this cost (Dalton et al., 2012).

Table 1. Breakdown of O&M cost of a typical offshore wind farm.

Categories	€/MWh	%
Maintenance	8.8	40.00
Administration	5.5	25.00
Insurance	3.3	15.00
Rent	3.3	15.00
Electricity	1.1	5.00
Total	22	100.00

The scheduled maintenance of wave and wind energy can be organised to be done at the same time or in continuous length of time, reducing the cost associated with the transport of maintenance staff and the boarding of personnel onto offshore structure. The same with the labour cost, because this covers the cost of the O&M staff, which will typically be stationed on the project full time, and so this can be shared for both installations. Taking this into consideration, the feasible cost-saving due to common strategies in maintenance tasks would achieve reductions up to the 12% (Astariz et al., 2015a).

4.3. Power smoothing

Wind speed fluctuates widely, and with wind power depending on the wind speed cubed, the variability in the power output of offshore wind farms is by no means negligible (Astariz & Iglesias, 2016). This variability can hinder the penetration of off-shore wind energy into the electricity market due to the resulting instability in the power system and the associated balancing costs. Diversified renewable systems have been proposed as a solution to achieve a smoother power output (Astariz & Iglesias, 2016).

The power production of offshore wind turbines and wave energy converters was compared to the combined power production (Astariz & Iglesias, 2016), with the objective of quantifying the reduction in variability that can be achieved through co-located wave-wind energy farms. This was investigated through two wind farms currently in operation, Alpha Ventus and Horns Rev 1. Wave and wind resources presented significant fluctuations throughout the year, with slightly lower variability in the case of Horns Rev. The correlation between both resources was low over significant parts of the year at Alpha Ventus, whereas waves and winds were better correlated at Horns Rev.

The output power of both wind farms was examined and, in addition to the power variability, the frequency of low wind speeds and the cut-in and cut-out wind speeds of the wind turbines resulted in a significant number of downtime hours in both wind farms. On this basis, the power output of co-located farms with different percentages of wave power installed was estimated.

At Alpha Ventus, the best performances were obtained for mostly composed farms. The most significant finding was that the combined power output was smoother and provided higher availability than the individual (wave only or wind only) power out-put (Figure 4): variability was reduced by up to 6% and non-operational period by up to 76% (Astariz & Iglesias, 2016).

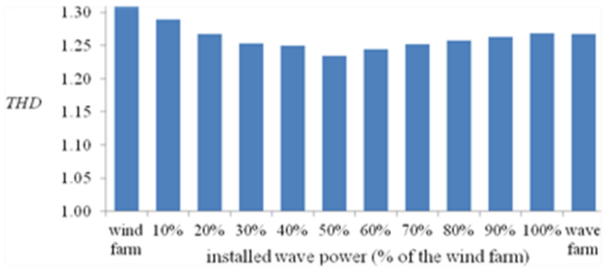

Figure 4. Variability of the annual power output in terms of the THD indicator during the study period for the combined farms at Alpha Ventus and Horns Rev.

Moreover, adding wave generation allowed for a more stable power output within a typical day. In other words, both the magnitude of the peaks and the high-frequency variability found in the individual power outputs reduced when these were combined. However, in the case of Horns Rev it was found that the complementarity between offshore wind and wave energy was smaller due to the high correlation between these resources. Indeed, the output power variability was not reduced in any significant manner with any of the co-located farms considered. Nevertheless, downtime did diminish very significantly (87%). The power capacity of the combined farms was also quantified. At Alpha Ventus the optimum combination in terms of power variability (50% mixed farm) presented also the maximum performance – the capacity factor in-creased around 6%. In the case of Horns Rev 1, the capacity factor increased by 3% for a 10% mixed farm.

To sum up, combined wave and wind energy farms reduce downtime in all cases and, consequently, are effective in preventing the sharp falls in the power supplied to the grid preceding downtime periods. With regard to the power variability, the weaker the correlation between wave and wind, the greater the benefits of their combination. This was reflected also when analysing the results into monetary terms, since an estimated operation cost reduction by 5% per year was found at Alpha Ventus and 2.5% at Horns Rev.

4.4. The shadow effect

The energy extraction of an array of Wave Energy Converters (WECs) creates a wake that modifies the local wave climate by reducing the mean wave height, which is known as the shadow effect. In previous works, the savings that could be achieved by enlarging the weather windows for O&M were estimated at 25 percent; which would lead to a reduction in the overall project cost of energy of 2.3 percent (Astariz & Iglesias, 2015c).

The analysis of the shadow effect provided by co-located WECs at the periphery of a wind farm was investigated in previous studies (Astariz & Iglesias, 2015a) through four real wind farms currently in operation, whose locations and characteristics are presented in Figure 5 and Table 2, respectively.

Figure 5. Location of the four wind farms: Alpha Ventus, Bard 1, Horns Rev 1 and Lincs.

Table 2. Characteristics of the offshore wind farms.

Wind farm	Depth (m)	Distance from shore (km)	Installed capacity (MW)	Number turbines	Area (km^2)
Alpha Ventus	33-45	56	60	12	4
Bard 1	39-41	90-101	400	80	59
Horns Rev 1	6-14	14-20	160	80	21
Lincs	8-16	8	270	75	41

The co-located wind-wave farms proposed were simulated using a third-generation numerical wave model: SWAN (Simulating WAves Nearshore), which was successfully used in previous works. Both the wind turbines and WECs were implemented in SWAN as individual obstacles characterised by a transmission coefficient with values ranging from 0% (i.e., 100% of incident wave energy absorbed) to 100% (Astariz & Iglesias,. 2015a). Two co-located WECs layouts (Table 3) were proposed taking into account the wind farm layouts, the wave climate, and the results of previous studies. In the first case (Figure 6a), the co-located WECs configuration consists of two main rows of WECs with a spacing of 198 m orientated towards the prevailing wave direction, and other rows of WECs at an angle of 45º to face secondary wave directions and thus protect a larger wind farm area. With the second configuration (Figure 6b) the aim is to check if deploying WECs in an arc can lead to a wave height reduction similar to that obtained with an angular layout with fewer WECs.

Table 3. Total Number of Co-located WECs and the Rate Between the Total Number of WECs and Wind Turbines (r).

Wind farm	Layout in angle		Layout in arc	
	Total	*r*	Total	*r*
Alpha Ventus	34	2.83	32	2.67
Bard 1	79	0.99	79	0.99
Horns Rev 1	55	0.69	53	0.66
Lincs	81	1.01	80	1

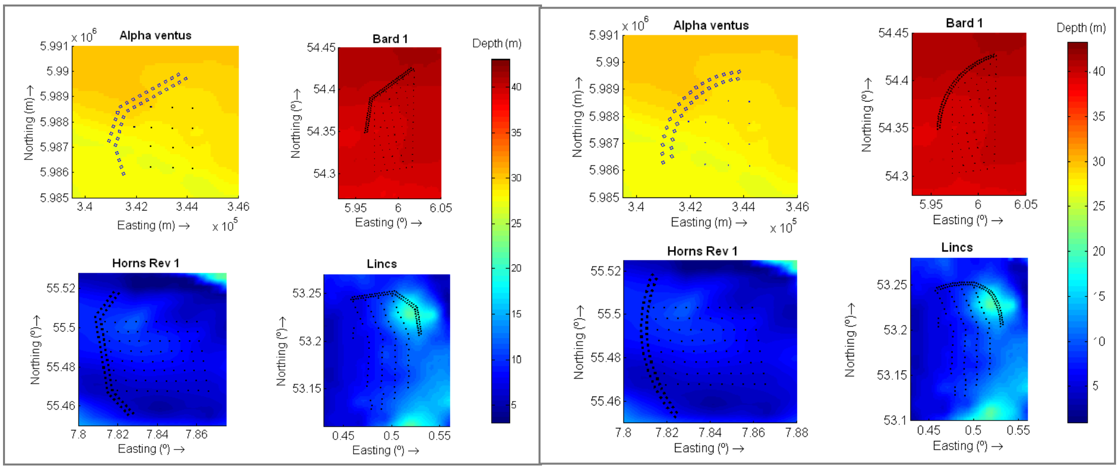

Figure 6. Co-located wind farm layouts with WECs: (a) at an angle. (b) in arc.

In the light of the results, the wave height reduction achieved throughout the farm (HRF) ranged between 13% and 19% (Table 4) and was always larger for the layouts with WECs deployed at an angle than for those in arc, although the difference between the results of both configurations was small (between 1 and 2%). Comparing the results between wind farms (Table 4), the best values were obtained for Bard 1, where a good interception of the incoming waves was achieved for the two layouts of co-located farms (Figure 7). These results were followed very closely by those obtained for Alpha Ventus and Horns Rev 1, whereas the wave height reduction achieved at Lincs was smaller. This was due to three main factors. First, the wind farm layout – this farm has a slightly elongated shape. Second, the wave direction has a greater variability than in the other case studies, and the farm remained unprotected against waves from secondary directions (Figure 8). For this reason a larger number of WECs would be required on the east side of the farm to achieve better results; however, this would imply an important increase in the ratio between the number of WECs and wind turbines, raising the final cost of the co-located farm. Third, the wave climate in this park, which was milder than in the other farms and, therefore, less wave energy could be extracted by the co-located WECs.

Table 4. HRF (%) Values achieved with co-located WECs deployed in angle or in arc based on the annual data series.

Wind farm	Layout	N_{WECs}	*HRF* (%)
Alpha Ventus	in angle	34	18
	in arc	32	17
Bard 1	in angle	79	19
	in arc	79	17
Horns Rev 1	in angle	55	17
	in arc	53	15
Lincs	in angle	81	14
	in arc	80	13

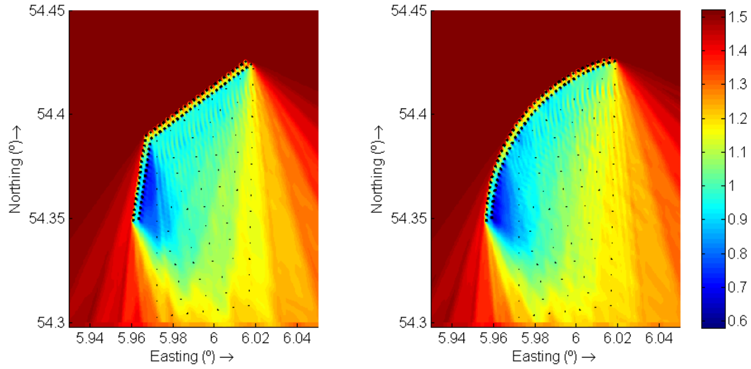

Figure 7. Wave height reduction obtained with co-located WECs at Bard 1 under a sea state with: H_s = 1.71 m, T_p = 6.09 s and θ = 230º. The colour scale represents the significant wave weight, H_s (m).

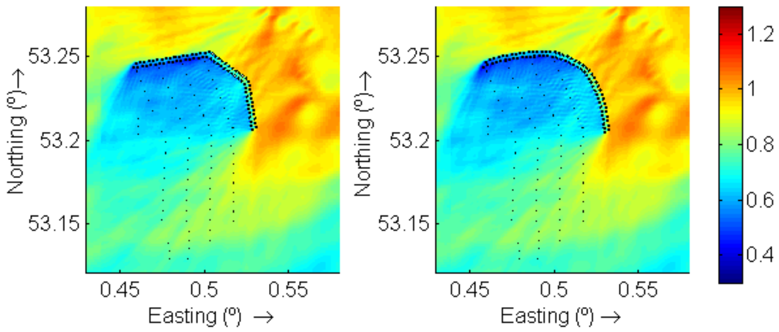

Figure 8. Wave height reduction due to co-located WECs at Lincs under a sea state with: H_s= 1.18 m, T_p= 6.03 s and θ= 60º. The colour scale represents the significant wave weight, H_s (m).

Furthermore, the results of Horns Rev 1 are particularly interesting since they were similar to those of the best scenario, even though the ratio between number of WECs and wind turbines in Horns Rev 1 is much lower than in the other cases – an important consideration for the economic assessment. The explanation lies in the geometry of the wind farms: the layout of Horns Rev 1 is close to a square, whereas Bard 1 or Lincs have a more elongated shape and therefore require more WECs for a similar degree of shelter.

As regards the accessibility to the wind turbines, it was below 82% for all the wind farms analysed, which corresponds to availability values below 90%. Nevertheless, an important increase of the accessibility was achieved by deploying co-located WECs along the periphery of the farm in the four case studies (Table 5). More specifically, the results for Alpha Ventus and Bard 1 were very similar, the accessibility increased ($\Delta T_{O\&M}$) by 17-18%, whereas in Horns Rev 1 this increased by 13-15% and in Lincs by 8%.

Table 5. Accessibility and $\Delta T_{O\&M}$ Values for the co-located farms considered.

Wind farm	Layout	Accessibility (%)	$\Delta T_{O\&M}$ (%)
Alpha Ventus	in angle	82.3	18.0
	in arc	82.2	17.8
Bard 1	in angle	69.7	18.2
	in arc	69.0	17.5
Horns Rev 1	in angle	70.9	15.6
	in arc	69.5	13.9
Lincs	in angle	81.3	8.9
	in arc	81.1	8.6

With regard to the influence of the co-located farm layout on the results, the arrays with small spacing between converters achieved the best results of wave height reduction. Moreover, the best results were obtained for co-located wave arrays that face both the prevailing and secondary wave directions, either with WECs deployed in angle or arc. Concerning the influence of the wind farm location, it was found that proximity to land is not a positive factor to implement co-located WECs, since it normally implies lower water depths and a milder sea climate, and consequently there is less available wave energy to be extracted by the WECs. The wind farm layout is another key factor – the largest wave height reduction was achieved for wind farms with square like geometries and smaller spacing between wind turbines, like Horns Rev 1.

4.5. The *Levelised Cost of Energy*

The economic feasibility of this mixed farm at Alpha Ventus was assessed through the levelised cost. According to Allan et al. (2011), the levelised cost in the Alpha Ventus wind farm is 156 €/MWh. In the case of the 50% mixed farm, the levelised cost was firstly calculated considering only the WECs as a stand-alone wave farm, and a value around 440 €/MWh was obtained, while it reduced about half the previous value, 220 €/MWh, when considering the co-located farm. Therefore, the initial development stage of wave technology involved greater energy cost, but this could be reduced by co-locating WECs within a wind farm. Moreover, the levelised cost was reassessed considering the expected learning curve for wave energy – a learning factor of 85-90% within the next 10 years is expected for wave energy (Dalton et al., 2010) – and a value by 160 €/MWh was obtained. The cost is almost the same as that of the baseline wind farm, but with the advantage of a more sustainable use of the resource, lower uncertainties about the availability and larger total power production.

5. CONCLUSIONS

The first aim of this paper was to present a general view of the economics of wave energy, a renewable which is still in its infancy but presents a large available resource. It was concluded that its offshore character – in most cases – along with the initial stage of development of the technology reduce the economic viability of wave energy, which may curb the development of this promising renewable technology. In this context, it was demonstrated that co-located wave and wind energy results in more convenient options than individual systems. The paper gave a glimpse into the different synergies that can be realised by these combined systems. Savings were identified in both capital and O&M costs. For the capital costs, reductions between 12 and 14% were achieved. As for the O&M costs, the first opportunity to achieve savings lays in common strategies, which would reduce O&M cost by 12%. In terms of power output, the combination of wave and wind energy results more convenient when both re-sources are not superimposed in time. When translated these results into monetary terms, it was concluded that co-located farms provide an excellent opportunity to increase the power production from renewables in a cost-competitive way, and to reduce supply uncertainties due to the variability inherent to the resource. Finally, it was concluded that implementing co-located WECs in wind farms could raise significantly the accessibility to the wind turbines. In fact, increases by up to 18% were found, reaching high levels of availability even over 90%.

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